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POST-TEST THERMAL-HYDRAULIC ANALYSIS OF TWO INTERMEDIATE LOCA TESTS AT THE ROSA FACILITY INCLUDING UNCERTAINTY EVALUATION

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Abstract

The OECD/NEA ROSA-2 project aims at addressing thermal-hydraulic safety issues relevant for light water reactors by building up an experimental database at the ROSA Large Scale Test Facility (LSTF). The ROSA facility simulates a PWR Westinghouse design with a four-loop configuration and a nominal power of 3423 MWth. Two intermediate break loss-of-coolant-accident (LOCA) experiments (Test 1 and 2) have been carried out during 2010. The two tests were analyzed by using the US-NRC TRACE best estimate code, employing the same nodalization previously used for the simulation of small-break LOCA experiments of the ROSA-1 program. A post-test calculation was performed for each test along with uncertainty analysis providing uncertainty bands for each relevant time trend. Uncertainties in the code modeling capabilities as well as in the initial and boundary conditions were taken into account, following the guidelines and lessons learnt through participation in the OECD/NEA BEMUSE program. Two different versions of the TRACE code were used in the analysis, providing a qualitatively good prediction of the tests. However, both versions showed deficiencies that need to be addressed. The most relevant parameters of the two experimental tests were falling within the computed uncertainty bands.

Introduction

Studies on pipe integrity have shown that the probability of a complete rupture of a pipe depends on the pipe size, and in particular that this probability is higher for smaller pipes [1]. Therefore, the double guillotine break of smaller pipes connected to the primary side of a pressurized water reactor (PWR) such as the surge line, the ECC line or the recirculation line (cold leg to pressurizer spray) should pose a more plausible scenario than a integral rupture of the cold or hot legs. The size of these pipes are mostly on the range in between small break (SB) LOCA and large break (LB)LOCA sizes and are designated as medium or intermediate break (IB) LOCAs. In addition, the United States Nuclear Regulatory Commission (USNRC) defined IBLOCAs as a design basis event in 2005 [2].

Best estimate system codes have been used to analyse the behaviour of nuclear power plants (NPP) under transient conditions. Integral test facilities have provided a large matrix of transient scenarios that have been used to validate and further develop system codes. However, the number of experiments which considered IBLOCA scenarios is small, so that the validation of system codes under these conditions is limited.

In this framework the NEA/OECD ROSA-2 project, which aims at resolving key light water reactor thermal-hydraulics safety issues, conducted two IBLOCA experiments at the ROSA/large-scale test facility (LSTF) of the Japan Atomic Energy Agency (JAEA). The ROSA/LSTF is a full-height and 1/48 volumetrically scaled test facility for system integral experiments simulating the thermal-hydraulic responses at full pressure conditions of a 1100 MWe-class. The reference plant is Unit-2 of

Tsuruga NPP of the Japan Atomic Power Company, a Westinghouse design [3]. In this paper, the two IBLOCA experiments (Test 1 and Test 2) carried out in 2010 at the ROSA/LSTF are analyzed by means of the USNRC system code TRACE.

In order to evaluate the capability of a system code to compute a given scenario, uncertainty analysis should be provided along with the best case calculation, in order to gain insight on the impact that small variations on the initial and boundary conditions or on the modeled parameters might have on the important time trends [4]. International benchmarks like BEMUSE [5] have been conducted to validate and compare different uncertainty methodologies. In this paper, the GRS SUSA methodology is used to evaluate the uncertainties of the simulation of Tests 1 and 2.

1. Methodology

1.1 TRACE nodalization of the ROSA facility

The TRACE nodalization of the ROSA facility had been derived on the basis of the TRAC-P and RELAP input decks provided by JAEA and the original geometry drawings. The nodalization was tested against two experiments of the ROSA-1 project, namely Test 6-1 [6] and Test 6-2, which consist of two small break LOCAs located at the upper head and the lower plenum of the reactor pressure vessel (RPV), respectively.

The TRACE model of the ROSA/LSTF, shown in Figure 1, consists of a 3-D vessel, two separate loops with two steam generators and a pressurizer. Further details on the nodalization can be found in ref. [6]. Two different TRACE versions are used in the present analysis: the consolidated 5.0 version TRACEv5.0 and the last released version TRACEv5.0patch2.

The counter current flow limitation (CCFL) model was activated in two locations:

- The top plate at the top of the core. The Wallis correlation was used with the coefficients specified in the BEMUSE project (m=1.0 and c=0.8625). [5]
- The SG's inlet plena (only for test 2). Again the Wallis correlation was used, although in this case the coefficients suggested by Yamamoto et al. [12] were used (m=1.0, c=0.75).

Both IBLOCA tests addressed in the present paper (Test 1 and Test 2) start from the same initial steady-state conditions. A comparison with the calculated values is shown in Table 1. The two TRACE versions (i.e. 5.0 and 5.0patch2) provided very similar results, in reasonable agreement with the experimental values.

Table 1 Normalized initial conditions of the ROSA tests compared to the TRACE calculations

Variable	Exp.	TRACE V5.0	TRACE patch2
Core power	1.0 ±0.012	1.0 ±0.017	1.0 ±0.017
Hot leg to DC bypass flow	1.0 ±0.2	1.37 ± 0.5	1.35 ± 0.5
Primary pressure	1.0 ±0.007	1.006 ± 0.013	1.005 ± 0.012
Hot leg fluid temperature	1.0 ±0.005	1.01 ± 0.002	1.01 ± 0.002
Cold leg fluid temperature	1.0 ±0.005	1.003 ± 0.001	1.003 ± 0.001
Mass flow rate	1.0 ±0.05	1.03 ± 0.04	1.03 ± 0.04

Main feedwater flow rate	1.0 ±0.02	0.99 ±0.01	0.99 ±0.01
Main steam pressure	1.0 ±0.007	1.0 ±0.0	1.0 ±0.0
Secondary side liquid level	1.0 ±0.04	0.96/0.94 ±0.01 m	0.95/0.95 ±0.01 m
Steam flow rate	1.0 ±0.04	0.99 ±0.01	0.99 ±0.01
Accumulator pressure	1.0 ±0.01	1.0 ±0.04	1.0 ±0.04
Accumulator level	1.0 ±0.04	1.0 ± 0.02	1.0 ± 0.02

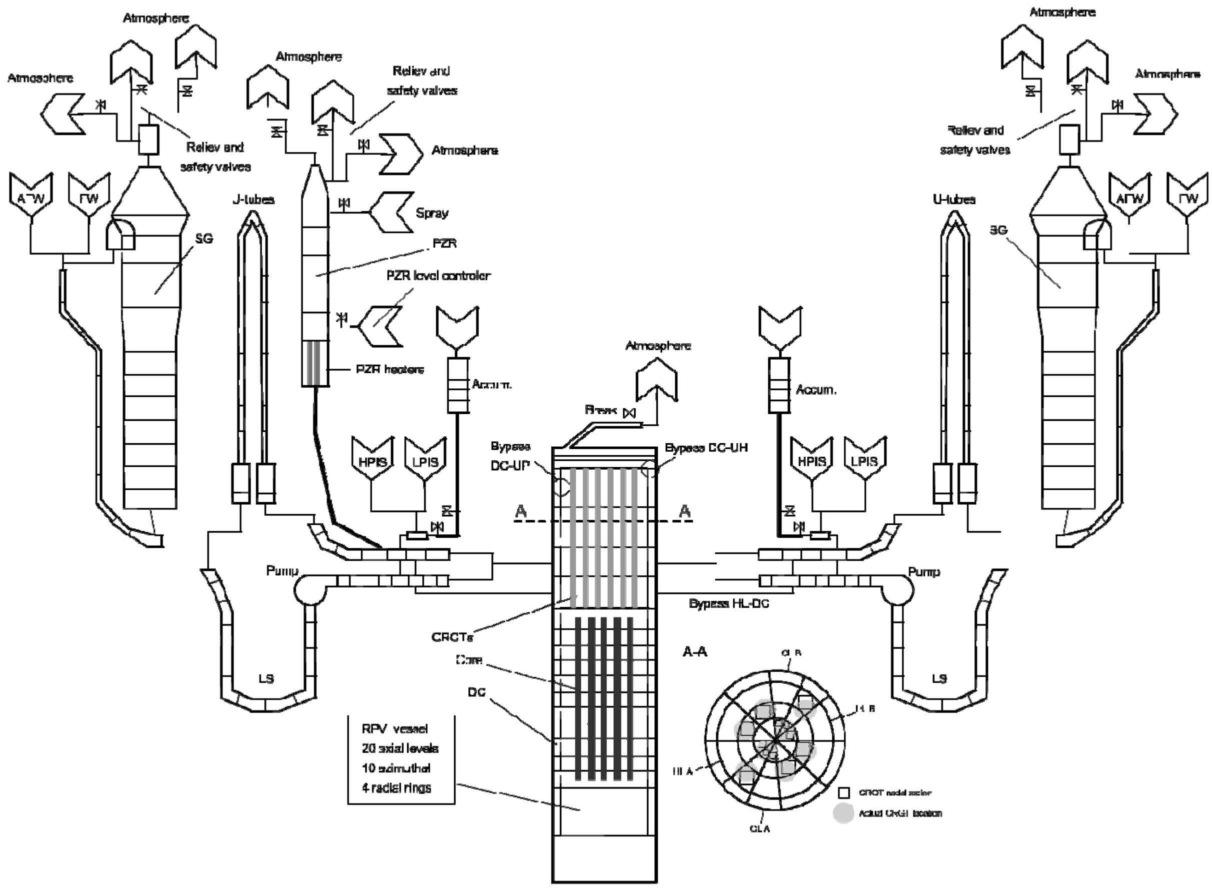

Figure 1 PSI TRACE nodalization of the ROSA/LSTF

1.2 Description of the uncertainty methodology

The GRS SUSA [7] methodology, which uses a name-order statistics for the Wilks formula [8], is employed to evaluate the uncertainties on the calculations presented in this work.

Based on experimental data and expert information, a list of uncertain parameters is defined. The uncertain parameters can be related to the physical models, the initial and boundary conditions, the material properties, etc.

Each uncertain parameter is considered as an input value with an associated probability density function (pdf). Once the parameters have been specified, a certain number (N) of sets of parameter's samples are randomly generated according to the pdf of each single parameter. These sets of parameter's samples are used to define N code runs of the same transient, each run corresponding to a parameters sample of the set. The Wilks formula gives the number N of runs to be performed in order to obtain an estimation of a given simulation output within an α-percentile with a β confidence level. The N values of the considered output parameter are ordered: Y(1) < Y(2)< Y(j) …< Y(N-1) < Y(N), where Y(j) represents the output parameters of the j-th simulation of the transient under analysis. On the basis of this ranking, a majoring value of the 95% percentile with a confidence level of 95% ($\alpha = \beta = 0.95$) is obtained by considering, as an example, Y(N-1), with N = 93: Wilks at the second order (r = 2).

17 parameters were taken into account in the uncertainty analysis reported in the present article, including material properties, model coefficients, and initial and boundary conditions. The distribution and variation range of the selected parameters were mainly based on the parameters specified during the BEMUSE project [5]. From the 20 parameters suggested within the phase V of the BEMUSE project, some parameters were discarded because they were not applicable to the present tests. For instance, hot rods are not modeled in the ROSA/LSTF facility, therefore all the hot rod related uncertainties were discarded. The friction form loss in the Accumulator line, taken into account within BEMUSE, was discarded after a sensitivity analysis carried out for the ROSA facility showed no significant effect on the transient results. The uncertainty on the U-tubes heat transfer area was used instead of the one on the initial intact loop cold leg temperature. Besides, uncertainty was considered for the RPV bypasses using the typical ranges and pdf for friction form loss coefficients recommended in BEMUSE. The accumulator liquid volume was included in the list of uncertain parameters since its uncertainty could be extracted from the experimental error specified in previous ROSA tests [9]. In addition, the uncertainty on the break discharge coefficients was taken into account as well; a different uncertainty range was selected for the two tests because the base case coefficients used in the two TRACE versions (5.0 and 5.0patch2) were not the same in the two cases (this issue is further analyzed and discussed in Section 4).

100 simulations were performed for the uncertainty analysis of both tests, and the probabilistic GRS method (SUSA) was used in order to propagate parameter uncertainties to the output variables. A list of the considered parameters, together with their uncertainty range and the type of pdf, is shown in Table 2.

Table 2 List of parameters used for the uncertainty analysis

Model-Parameter	**Range**		**Distribution**
	Test 1	**Test 2**	
Fuel Thermal Conductivity	0.9 ~ 1.1 (Tf < 2000 K)		Normal
Fuel Heat Capacity	0.98 ~ 1.02 (Tf < 1800 K)		Normal
Power after Scram	0.92 ~ 1.08		Normal
Initial Core Power	0.98 ~ 1.02		Normal
Rotational Speed of Pump after Break	0.98 ~ 1.02		Normal
Flow rate characteristics of LPI	0.95 ~ 1.05		Normal
Initial Accumulator Pressure	-0.2 ~ +0.2 MPa		Normal
Initial primary Pressure	-0.2 ~ +0.2 MPa		Normal
Initial Intact Loop Mass Flow Rate	0.96 ~ 1.04		Normal
U-tubes Heat transfer area	heat transfer area +-15%		Normal
Liquid Volume in Accumulator	0.9 ~ 1.1		Normal
Discharge Coefficients	0.7-1.1	0.8-1.2	Normal
Bypass UP-DC (K-factor)	0.5-2.0		Lognormal

Bypass UH-DC (K-factor)	0.5-2.0		Lognormal
Bypass HL-DC (K-factor)	0.5-2.0		Lognormal
CCFL coefficient (SG plena)	Not used	0.6-0.9	Normal
CCFL coefficient (top of core)	0.69-1.035		Normal

2. Test 1, hot leg intermediate break LOCA

Test 1 is an intermediate break LOCA transient that supposes a complete rupture of the surge line and the unavailability of the high pressure safety injection (HPSI) system. The test is started by isolating the pressurizer and by opening the break valve located in the hot leg. Since a large amount of coolant is released through the break, the primary pressure and the RPV water level plunge. At the time when the hot leg of the broken loop becomes empty and the break flow conditions switch from two-phase flow to single-phase vapor flow, the coolant that remains in the core starts to flash and the core level is further reduced. An increase in the cladding temperature occurs as the heater rods become uncovered. Almost at the same time, the accumulator's (Acc) valves open since the primary pressure has dropped below the Acc set-point. When the core water level starts to rise, a large amount of steam is produced in the core, so that the pressure difference between the upper plenum (UP) and the downcomer (DC) increases, and hence, a loop seal (LS) clearance occurs. The core is refilled by means of the Acc's injection and the LS clearance. The timing between these three phenomena (Acc's injection, LS clearance and break flow conditions) will define the height of the peak cladding temperature (PCT).

2.1 Analysis of the results

The most relevant results of Test 1 are shown in Figures 2 and 3 where the two TRACE versions are compared with the experiment. The uncertainty bands were obtained by using the V5.0 version. Exactly the same input deck was used with the two code versions. Figure 2 shows the primary and secondary pressures, the break mass flow and the accumulator's flow, while in Figure 3 the results obtained for the peak cladding temperature and the DC and core water levels are reported. The choked flow coefficients used at the break location for this test were: 1.0 for the subcooled coefficient and 0.85 for the two-phase coefficient. The break mass flow was slightly over predicted by TRACE even though a two-phase discharge coefficient of 0.85 was used for the choked flow model (TRACE uses a Choked model based on the Ransom-Trapp model [10,11]). The primary pressure was very well predicted once the discharge coefficient was reduced.

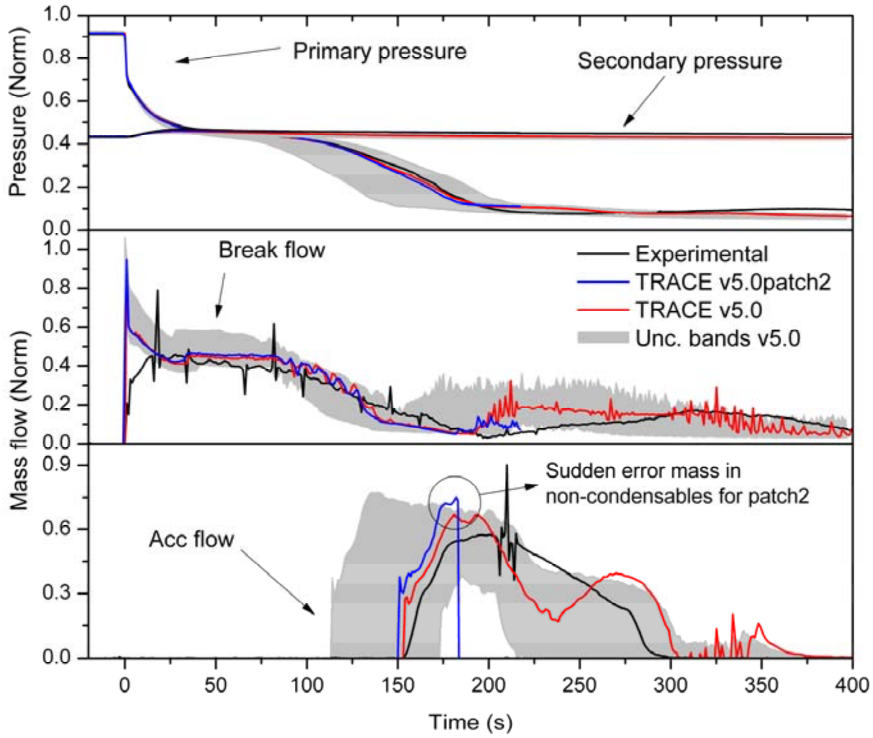

Figure 2 TRACE results of Test 1 compared with the experiment. From top to bottom: Primary and secondary pressures, break flow and Acc flow. The uncertainty envelope is shown in grey colour.

The maximum PCT was also in accordance with the experiment (Figure 3); however the maximum temperature was found at different elevations in the experiment and in the simulations (around 1 meter difference). A good agreement was obtained for the water level in both the DC and the core, as shown in Figure 3. In addition, the uncertainty bands contained the experimental results during the relevant periods of time. The two calculations performed with TRACE 5.0 and 5.0patch2 respectively showed comparable results, although the last TRACE version (5.0patch2) exhibited an unphysical behaviour of the non-condensable gases in the accumulator at around 180 seconds (see Figure 2). In particular, it was observed that the total mass of non-condensable gases dropped suddenly and thus, the accumulator injection was interrupted temporarily because the pressure at the accumulator became suddenly lower than the system's pressure. Consequently, the results obtained with patch 2 after this time of the transient cannot be taken into account in the evaluation.

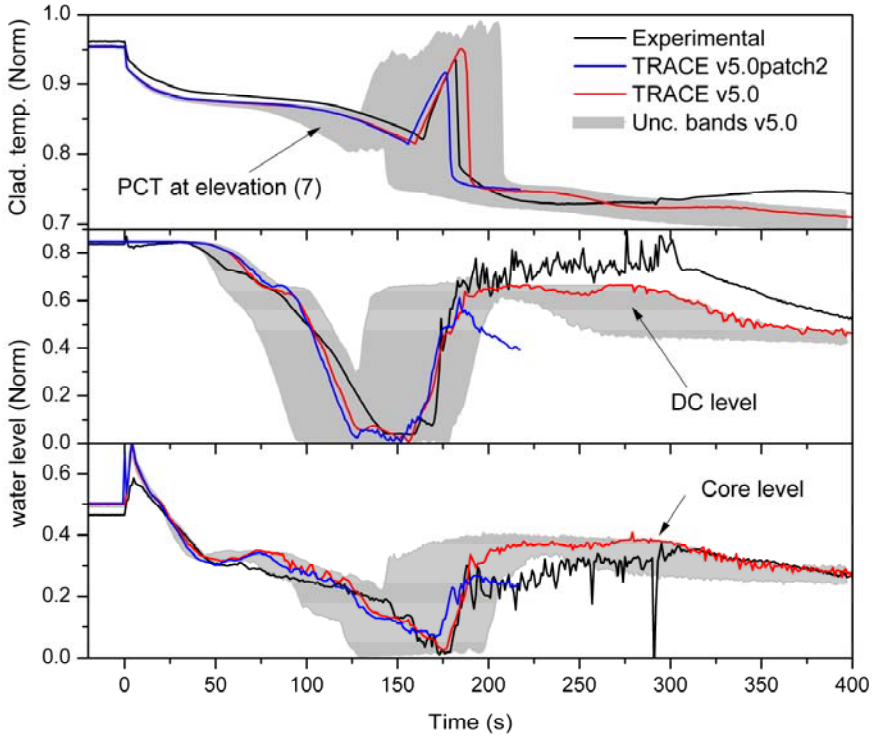

Figure 3 TRACE results of Test 1 compared with the experiment. From top to bottom: Cladding temperature at elevation 7, DC water level and core water level. The uncertainty envelope is shown in grey colour.

3. Test 2, cold leg intermediate break LOCA

Test 2 is an IBLOCA transient that supposes a complete rupture of the emergency core cooling (ECC) line connected to the cold leg. The 17 % break, corresponding to the volumetrically-scaled cross-sectional area of the reference PWR cold leg, was simulated in the experiment by using a nozzle mounted on the top of the cold leg (upward direction). Since the transient of study supposes the rupture of the ECC line, the ECC system was actuated only in the intact loop. The failure of a diesel generator was also assumed. Considering that the test intends to simulate a 4-loop Westinghouse design transient, the HPSI and low pressure safety injection (LPSI) flows injected to the intact loop will correspond to 3/8 of the total nominal flow because, from the nominal 8 available pumps (2 per each cold leg), four are lost due to the failure of the diesel generator and an extra one is lost because of the ECC line rupture. The Acc's volume to be injected in the intact loop will correspond to the volumetrically-scaled volume of three Accs of the reference plant.

The test was started by opening the break and was characterized by the actions usually taken after the scram signal was reached, namely: initiation of core power decay, initiation of primary coolant pumps coastdown, turbine trip, closure of main steam isolation valve and termination of main feedwater.

3.1 Analysis of the results

The most relevant results of Test 2 are displayed in Figures 4 and 5, where the results obtained with the two TRACE versions are reported together with the experimental results. The uncertainty bands displayed were again obtained by TRACE v5.0.

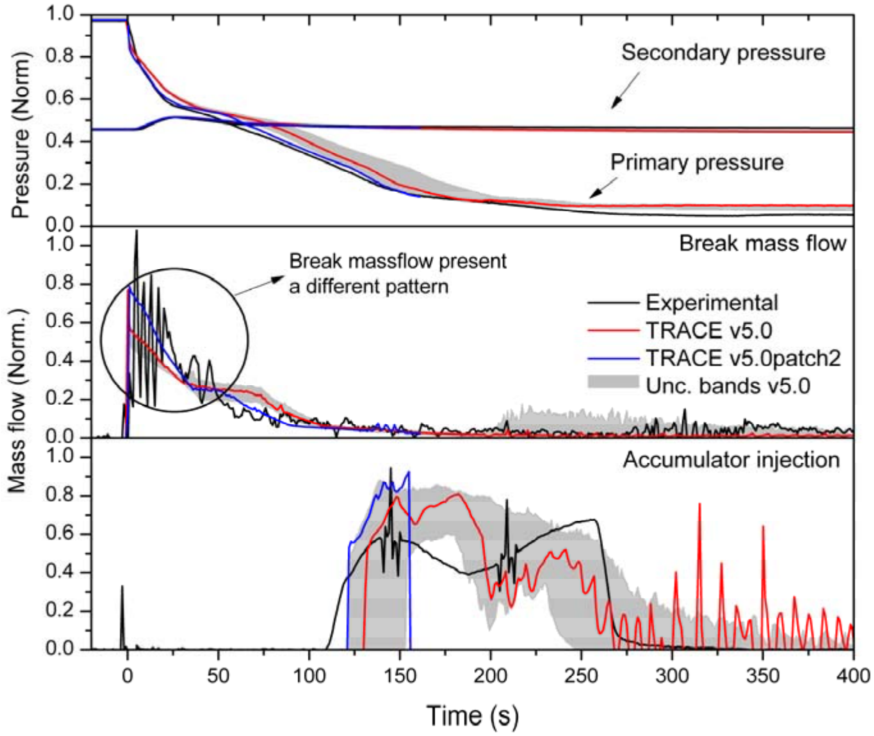

Figure 4 TRACE results of Test 1 compared with the experiment. From top to bottom: Primary and secondary pressures, break flow and Acc flow. The uncertainty envelope is shown in grey colour

The primary and secondary pressures (top of Figure 4) presented a good agreement with the experiment, although the primary pressure was slightly over-predicted by v5.0 and under-predicted by patch2; the reason for these differences was found to be the choked flow model, which presented a different performance in the two code versions.

The choked flow coefficients used at the break for this test (when using the v5.0 version) were 1.0 for the subcooled discharge coefficient (C_s) and 1.1 for the two-phase flow discharge coefficient (C_{2p}), these values were different from those used in Test 1. A C_s of 1.0 and a C_{2p} of 0.85 had been used for Test 1. On the other hand, the patch2 base case calculations of both tests were carried out with the same discharge coefficients (a C_s of 1.0 and a C_{2p} of 0.85). The use of different C_{2p} in the v5.0 best cases is further explained in Section 4. As shown in Figure 4, the break mass flow presented a slightly different pattern from the experiment, especially with the results obtained by v5.0, which underestimated the break flow during the subcooled phase and provided a longer two-phase flow phase. Later it was found that the subcooled section of the choked flow model in v5.0 presented deficiencies in its logic in comparison to the patch2 version (see section 4 for further details).

The accumulator flow (bottom graph of Figure 4) followed a similar time trend as in the experiment when using v5.0, however the same problem as for Test 1 with the non-condensable mass conservation was encountered by using patch2 (see the bottom graph of Figure 4 at around 155 seconds).

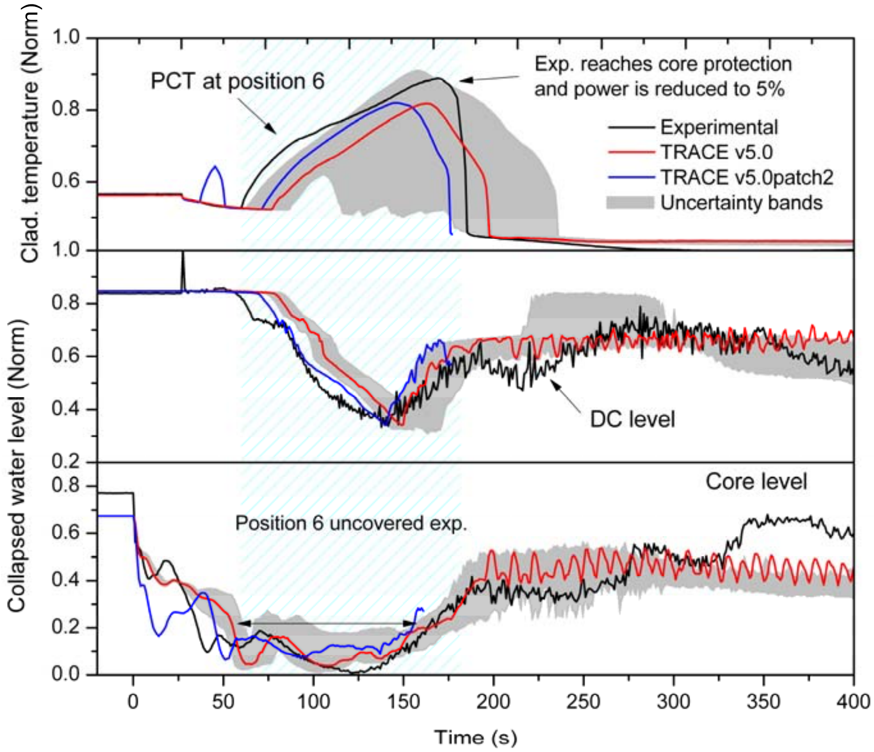

Figure 5 TRACE results of Test 1 compared with the experiment. From top to bottom: Cladding temperature at elevation 6, DC water level and core water level. The uncertainty envelope is shown in grey colour.

Figure 5 shows (from top to bottom): the cladding temperature at elevation 6, the water level in the downcomer and the core water level. The cladding temperature presented similar results for the two code versions. The PCT was underestimated by around 30 degrees (v5.0) and 35 degrees (patch2) respectively. Overall, the water levels in the RPV were reasonably well predicted by both TRACE versions. However, as indicated in Figure 5, the time window during which the heated rods were uncovered was slightly longer in the experiment, and therefore the PCT was under predicted by both code versions.

Due to the problems encountered with the choked flow when running Test 2 with v5.0, the uncertainty analysis was carried out a second time by using the patch 2 version. The uncertainty bands obtained with TRACE 5.0patch2 are compared with those obtained with v5.0 in Figure 6.

The effect on the break flow during the first 40 seconds of the transient resulted in a much wider uncertainty bands during this period for both the break mass flow and the core water level. Therefore, the maximum PCT uncertainty band became wider and the maximum temperature obtained was 100 K higher than the maximum experimental value, giving a margin of confidence to ascertain that even if the core protection would have not been activated the temperature would still be kept within the uncertainty range. The uncertainty bands provided by patch 2 clearly bounded all the important parameters.

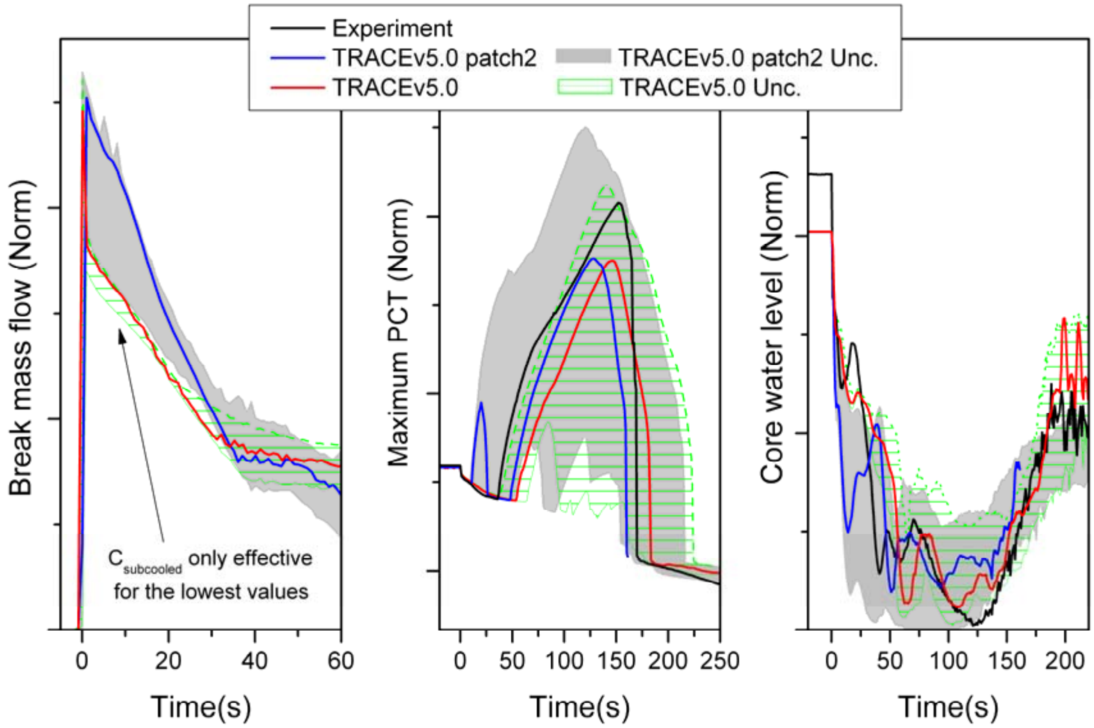

Figure 6 Comparison between the uncertainty analyses results using two different TRACE versions

4. Code versions, issues and differences

The v5.0 version of the TRACE code has been used for all previous simulations performed at the Paul Scherrer Institute (PSI) with the ROSA/LSTF model and presented a good agreement with the experiments. However, the disagreement of the choked flow patterns obtained for Test 2 and especially the need to use different discharge coefficients than those used for Test 1 to correctly capture the experimental results, has forced us to test the latest release of the TRACE code (namely TRACE5.0patch2). Even though small modifications on the discharge coefficients are generally accepted by the international community, these changes must be consistent and not arbitrarily performed by the code user depending on the specific case to be calculated (unless the break conditions and geometry are very different). The differences observed between Tests 1 and 2 indicated that a revision of the choked flow of TRACE was required. Once the same nodalization was tested with newer versions of the code (patch 2), it was found out that the choked model was providing indeed a much better agreement with the experiment. Further studies focused on Test 2 indicated that by using v5.0, the subcooled choked flow (first 40 seconds of transient) was limited within the code so that variations of the subcooled discharge coefficient would not have any measurable impact on the results. As a matter of fact, a close look at the left graph of Figure 6 indicates that the uncertainty band for the break flow during the subcooled phase was almost negligible, especially when compared to the uncertainty band calculated for 5.0patch2. In particular, it was found that the subcooled discharge coefficient influenced the results only when values under 0.85 where selected (all calculations carried out by selecting a higher coefficient were equivalent with those obtained with patch 2 and a coefficient of 0.85). This limitation in version 5.0 has a strong effect on the subcooled flow uncertainty band. Since the resulting break flow was much lower during the subcooled phase, a higher value for the C_{2p} was needed to compensate the total discharged mass. This explains the differences between the C_{2p} used in the two tests for the v5.0. This adjustment was not necessary for the patch2 version.

The problem with the subcooled part of the choked flow model have been solved in patch 2, however other issues have arisen with this version. First of all, the computational time has increased considerably and, many of the runs carried out to obtain the uncertainties for patch 2 failed and it was needed to rerun them with much smaller time steps (down to 5.0×10^{-4}s). In addition, patch 2 presented a sudden error on the non-condensable mass conservation equation. This occurred in all runs at some point within the period of time between 125 and 200 seconds. This issue should be addressed since it affects transients with accumulator injection.

5. Conclusion

Two post test analysis of two IBLOCA experiments performed at the ROSA/LSTF facility within the OECD/NEA ROSA-2 project have been carried out by using the TRACE code. Firstly, the TRACE v5.0 version was used providing a reasonable agreement with the experimental data. However, the performance of the choked flow differed from the experiment. Uncertainty bands were also obtained in order to evaluate the quality of the calculation. Most parameters were contained within the uncertainty bands, even though for Test 2, the maximum PCT upper uncertainty band was only 20 degrees above the experimental value. Secondly, since the choked flow had been updated with the last released TRACE version (patch 2), the two post-test calculations were run again by using patch 2. The choked flow with patch 2 presented consistent results when analysing both Test 1 and Test 2. The uncertainty evaluation was performed again for Test 2 by using the patch 2 version. As expected, due to the better performance of the chocked flow model in patch2, much wider uncertainty bands were calculated so that the maximum PCT of the uncertainty bands was 100 degrees above the experimental value. On the other hand, new issues arose by using the last released version, namely an error on the non-condensables mass conservation equation and a lack of stability. These problems should be addressed in the future.

6. Acknowledgments

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